



Materials Challenges In Space Exploration

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Materials Challenges in Space Exploration



Overview

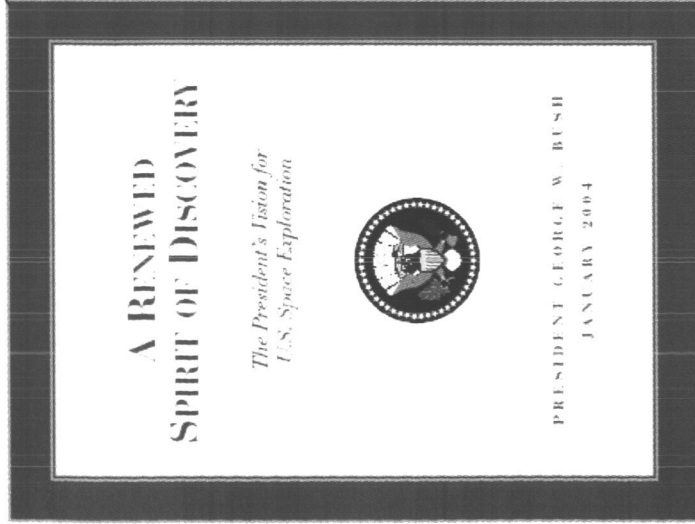
- **New Vision for Space Exploration**
- **Key Elements of the Space Exploration Vision**
- **Technology Framework for Exploration**
 - **Technology Readiness Levels**
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- **Materials Challenges in Space Exploration**
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 - **Vehicle Structures and Thermal Protection Systems**
 - **Space Systems**
 - **Integrated Vehicle Health Monitoring**
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- **Summary**



The New Vision for Space Exploration



- On January 14, 2004, President Bush articulated a new Vision for Space Exploration in the 21st Century
- The Fundamental Goal Of This Vision Is To Advance U.S. Scientific, Security, And Economic Interest Through A Robust Space Exploration Program



- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.



The Key Elements of Space Exploration Vision



1. Return the Shuttle to safe flight as soon as practical, based on CAIB recommendations
2. Use Shuttle to complete ISS assembly
3. Retire the Shuttle after assembly complete (2010 target)
4. Focus ISS research to support exploration goals; understanding space environment and countermeasures
5. Meet foreign commitments
6. Undertake lunar exploration to support sustained human and robotic exploration of Mars and beyond
7. Series of robotic missions to Moon by 2008 to prepare for human exploration
8. Expedition to lunar surface as early as 2015 but no later than 2020
9. Use lunar activities to further science, and test approaches (including lunar resources) for exploration to Mars & beyond
10. Conduct robotic exploration of Mars to prepare for future expedition



The Key Elements of Space Exploration Vision



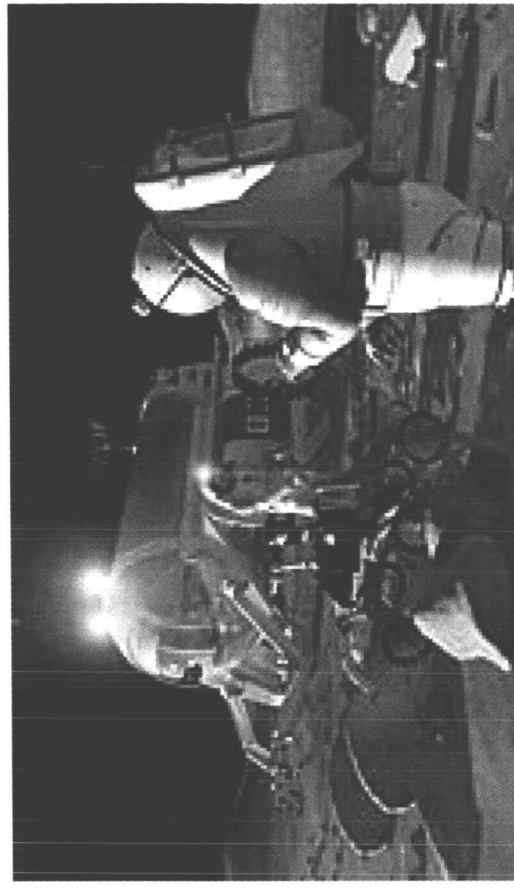
11. Conduct robotic exploration across solar system to search for life, understand history of universe, search for resources
12. Conduct advanced telescope searches for habitable environments around other stars
13. Demonstrate power, propulsion, life support capabilities for long duration, more distant human and robotic missions
14. Conduct human expeditions to Mars after acquiring adequate knowledge and capability demonstrations
15. Develop a new Crew Exploration Vehicle; flight test before end of decade; human exploration capability by 2014
16. Separate cargo from crew as soon as practical to support ISS; acquire crew transport to ISS after Shuttle retirement
17. Pursue international participation
18. Pursue commercial opportunity for transportation and other services



Missions to the Moon



- 2008: Initial flight test of a Crew Exploration Vehicle (CEV)
- 2008: Launch first lunar robotic orbiter
- 2009-2010: Robotic mission to lunar surface
- 2011 First Unmanned CEV flight
- 2014: First crewed CEV flight
- 2015-2020: First human mission to the Moon

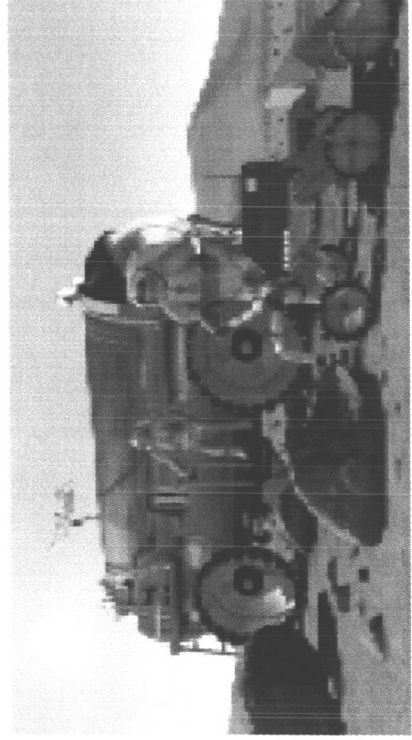




Preparing for Mars Exploration



- **Moon as a test bed to reduce risk for future human Mars missions**
 - **Technology advancement:** to reduce mission costs and support expanded human exploration
 - **Systems testing and technology test beds:** to develop reliability in harsh environments.
 - **Expanded mission and science surface operations:** to gain experience and develop techniques
 - **Human and machine collaboration:** Machines serve as an extension of human explorers, together achieving more than either can do alone.
 - **Breaking the bonds of dependence on Earth:** (e.g./Life Science/Closed loop life support tests)
 - **Power generation and propulsion:** development and testing
 - **Common investments:** in hardware systems for Moon, Mars and other space objectives





Technology Framework for Exploration

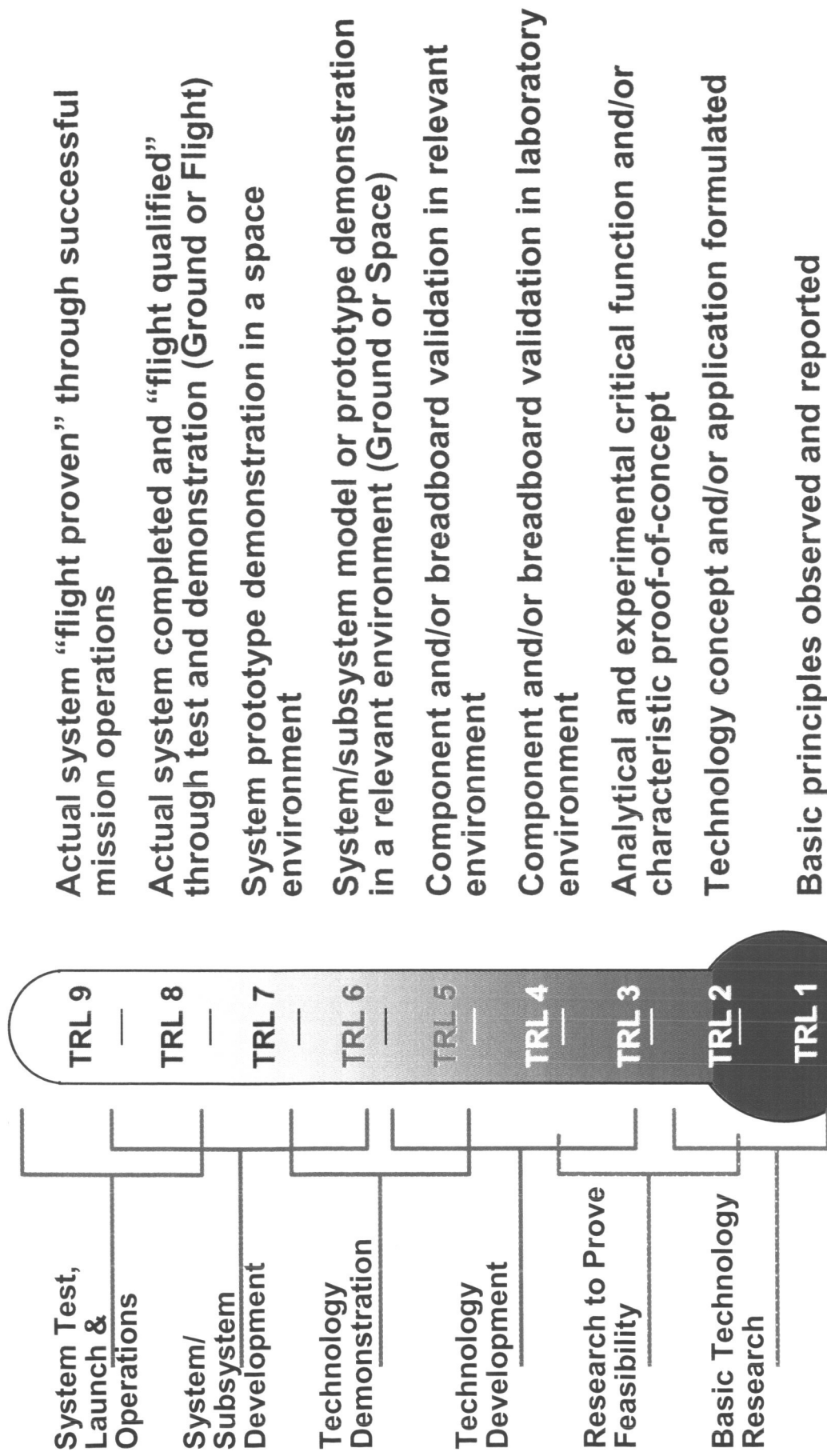


- Technology development is driven by mission requirements
- Technologies must be developed in a timely but affordable manner
- Technology development and maturation generally occurs in a five-step process:
 - Step 1: Basic research
 - Step 2: Supporting advanced space technology research
 - Step 3: Focused technology maturation
 - Step 4: System development project
 - Step 5: Flight mission project – final step
- Cycles of Innovation and Spiral Development
 - Systems are developed in such a way that they represent ‘building block’ capabilities for future missions– both human and robotic
 - Technologies will be inserted as they mature into development projects
 - The projects will be developed in a spiral fashion-- first spiral, second spiral, and so on. Each spiral represents a major advancement in technology and capability
 - The first spiral will be the Crew Exploration Vehicle



Technology Maturation Process

Technology Readiness Levels (TRLs)





Materials Technologies Maturation Process – Capability Readiness Levels (CRLs)



CRL 9	Material successfully demonstrated, possibly to failure, in a full-scale flight system and verified with nondestructive examination, microscopy, and possibly destructive property testing. ...
—	
CRL 8	Material successfully demonstrated, possibly to failure, on a full-scale system ground testing (entire engine) and verified with nondestructive examination, microscopy, and possibly destructive property testing. ...
—	
CRL 7	Material successfully demonstrated, possibly to failure, on a full-scale subsystem (portion of engine) in a representative, actual environment and verified with nondestructive examination, microscopy, and possibly destructive property testing. ...
—	
CRL 6	Material successfully demonstrated, possibly to failure, on a subscale in a combined loads, relevant environment (new demonstrator for specific end use application), and verified with nondestructive examination, microscopy, and possibly destructive property testing. ...
—	
CRL 5	Material successfully demonstrated, possibly to failure, on sub-element or subscale component in a combined loads, representative environment (existing demonstrator or simulator), and verified with nondestructive examination, microscopy, and possibly destructive property testing.
—	
CRL 4	Material successfully tested, possibly to failure, on sub-element shapes completed for simple load condition and verified with nondestructive examination, microscopy, and possibly destructive property testing. ...
—	
CRL 3	Key material properties achieved relative to desired requirements and basic material understandings, and then correlated to microscopy and analytical evaluation. ...
—	
CRL 2	Have preliminary understanding of material structure and the effect of processing variables on material characteristics to enable a material to be made with the desired characteristics. ...
—	
CRL 1	Idea/possibility assessment generated for new material, material system, or process. ...

**Materials and processes have to be sufficiently mature before
they can be used in system development**



Materials Challenges in Space Exploration



- **Materials and Processes generally fall into two categories**
 - **Existing materials and processes-- developed and proven**
 - **New and advanced materials and processes-- in development, not yet proven, but show promise of improved performance or life, lower weight, etc.**
- **Use of existing materials presents lower risk and cost**
- **Advanced materials pose higher risk but also present higher pay-offs in terms of performance, weight, life and reliability of space systems**
- **Materials Technologists need to mitigate the risk while preserving the pay-off at an affordable cost**



Materials Challenges in Space Exploration



- **Materials Selection Criteria**
 - Performance factors: lightweight, high strength, etc.
 - Environmental factors: space environment, radiation effects, elevated temperature
 - Manufacturability
 - Affordability
 - Availability
- **Application Areas**
 - Propulsion Systems – chemical and nuclear
 - Structures and Thermal Protection Systems
 - Space Systems– spacecrafts, space suits, habitats
 - Integrated Vehicle Health Monitoring (IVHM)
 - In-situ Materials Utilization



Materials Challenges in Space Exploration



Propulsion systems push materials to their limits

• Material Failure Mode

- Gross yielding
- Buckling
- Creep
- Brittle fracture
- Fatigue, low cycle
- Fatigue, high cycle
- Contact fatigue
- Fretting
- Corrosion-- galvanic
- Stress corrosion cracking
- Hydrogen embrittlement
- Oxidation/combustion
- Wear
- Thermal fatigue
- Corrosion fatigue

Relevant Properties

Yield strength (YS), shear YS
Compressive yield strength (C-YS), modulus of elasticity
Creep rate
Impact energy, transition temperature, K_{IC}
Fatigue properties, ductility
Ultimate tensile strength (UTS), fatigue properties
Compressive yield strength (C-YS)
C-YS, Electrochemical potential
Electrochemical potential
UTS, KISCC, electrochemical potential
UTS, chemistry
Chemistry
Hardness
Coefficient of thermal expansion, creep rate
Fatigue properties, electrochemical potential



Materials Challenges in Space Exploration



Ideal Material properties

- High yield and ultimate strengths and ductility
- High fracture toughness
- High threshold stress intensity (K_{th})
- High fatigue endurance limit
- Low crack growth rate (da/dN)
- Good capability for a broad range of temperatures
- Lightweight
- Corrosion resistance
- Insensitive to embrittlement (liquid metal, hydrogen, etc.)
- Homogenous – less variability in properties
- Isotropic – same properties in all directions
- Conductivity – high or low depending on application
- Radiation (cosmic/nuclear) resistance
- Non-degradable with age
- Reproducible properties
- Manufacturability —machineability, weldability, repairability, inspectability
- Affordability

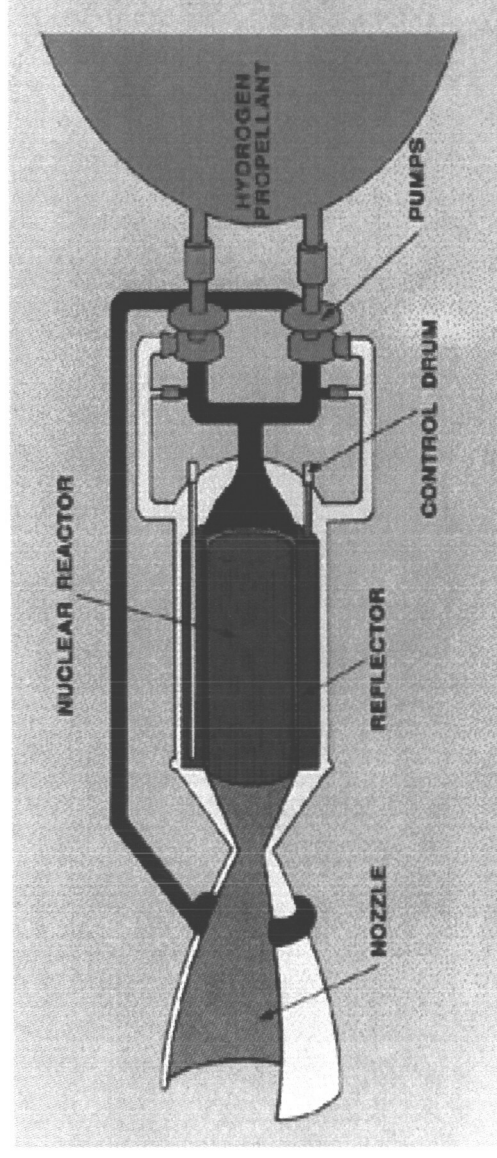


Materials in Nuclear Propulsion Systems



- Nuclear propulsion Systems
 - Nuclear electric system uses radio-isotope thermoelectric generator (RTG)
 - Nuclear Thermal Propulsion (NTP) system uses a fusion reactor (see schematic below)
- Materials Challenges
 - High temperature materials for fuel and heat exchanger-- $> 2500\text{K}$
 - High temperature materials for ducts, thrust chambers and nozzle
 - Reaction with containment materials
 - Hydrogen reaction & embrittlement
 - Radiation shielding– neutron absorption
 - Heat exchanger materials – thermal conductivity, emissivity

Schematic of a nuclear thermal propulsion system





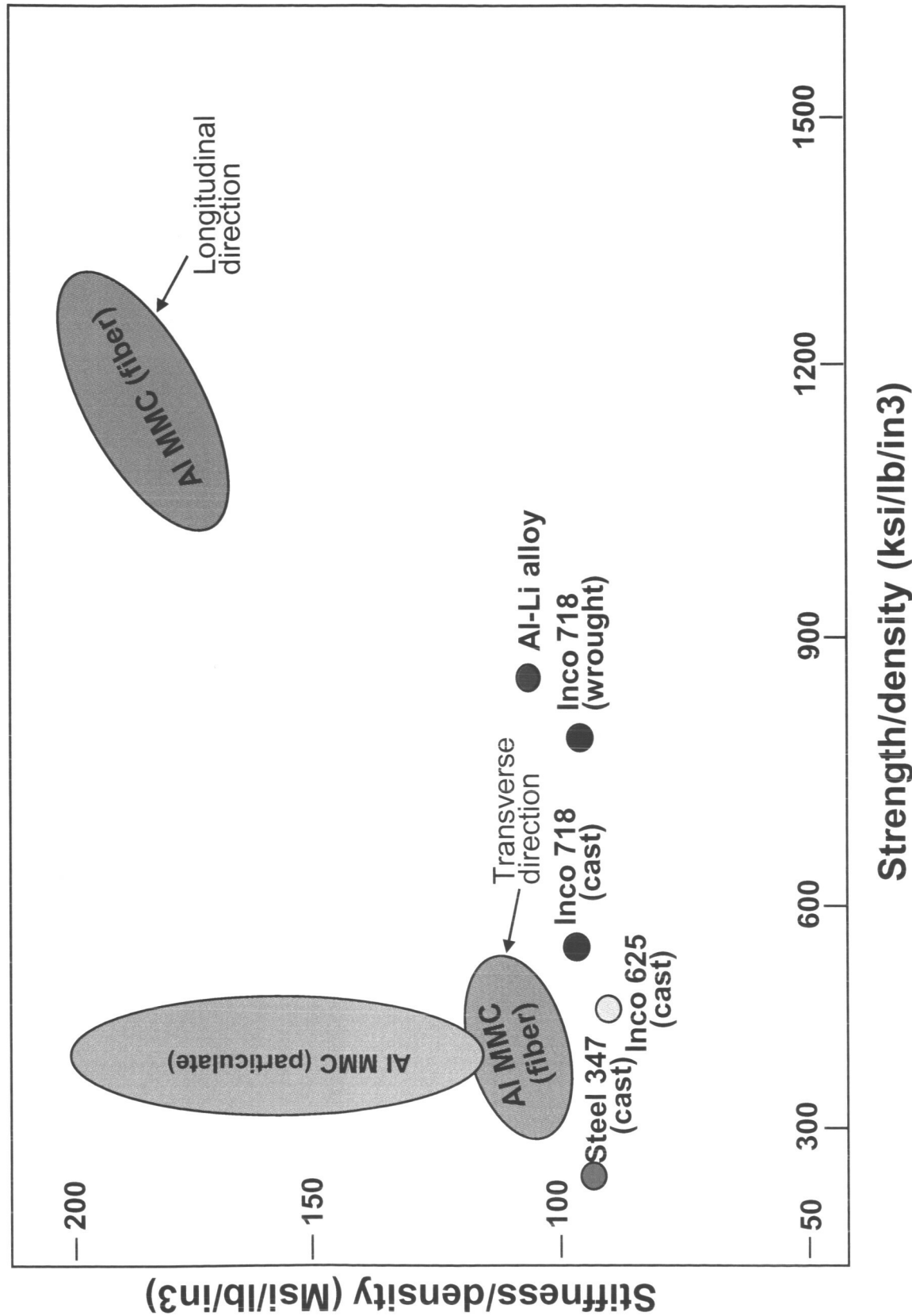
Materials in Structures and Thermal Protection Systems



- **Materials Challenges**
 - Availability of materials properties in the application environment
 - Lightweight & high strength
 - High stiffness
 - Manufacturability
 - Repairability
 - Cost
- **Common structural materials– for vehicles and cryogenic tanks**
 - Aluminum and titanium alloys
 - Steels
 - High strength nickel-base alloys
 - Polymer Matrix Composites (PMCs)– carbon-epoxy
 - Metal Matrix Composites (MMCs) – $\text{Al-Al}_2\text{O}_3$
- **Common TPS materials – for reentry and aerobraking**
 - Silica-based
 - Carbon-based: C-C, C-SiC
 - Alumina-based
 - Metallic
- **Cryogenic Insulation Materials – for cryogenic tanks**
 - Foam insulation



Specific Stiffness vs. Specific Strength

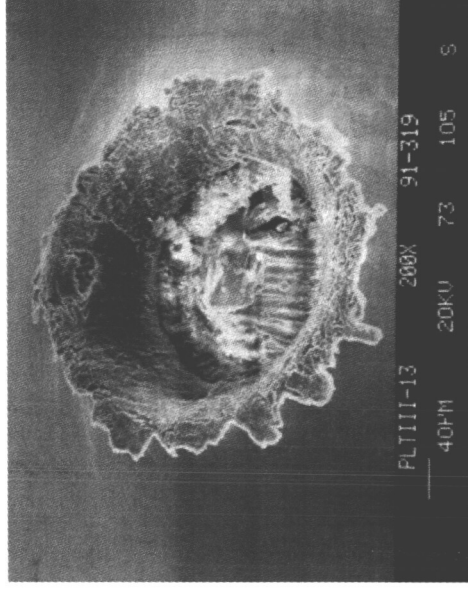
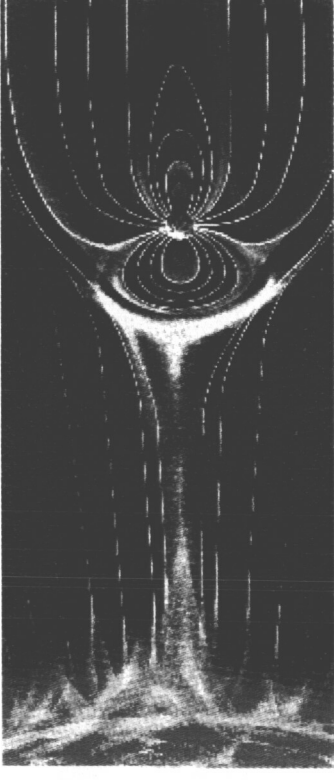




Materials in Space Systems



- Space Systems include spacecrafts, space suits and habitats in space and on the Moon
- Materials are exposed to harsh environment of space
 - Solar ultra-violet flux
 - Solar wind
 - Atomic oxygen
 - Space vacuum
 - Galactic cosmic radiation
 - Plasma charging
 - Micrometeoroid/space debris
 - Spacecraft induced environment
 - Contamination
- Materials can degrade in space environment
 - Adversely affect spacecraft and its performance



Micrometeoroid debris crater



Materials in Space Systems



Space Environmental Effects on Materials

	Atomic Oxygen	UV Radiation	Particulate Radiation	Plasma	Contamination
Metals	Oxides form; silver and osmium eroded	No significant effect	High levels degrade mechanical properties	Charging and arcing may occur on anodized surfaces	Reduces bonding to surfaces
Ceramics	Erosion/mass loss	Some darkening	Compaction may occur	Charging and arcing may occur	Reduces bonding to surfaces May cause severe degradation of optical properties
Optics	Oxides form on thin metallic reflector layers	Silica glass darkening	Compaction may occur; Darkening	Charging and arcing may occur	Reduces bonding to surfaces; outgassing source
Composites	Binders erode, graphite fibers generally erode at slower rate, fiberglass unaffected	Darkening of fiberglass	High levels affect glass transition temperature, strength		
Solar Cells	Attacks silver of electrical connectors With few exceptions, severe erosion occurs	Some darkening of cover sheet	Some degradation of power output Darkening, embrittlement	Arcing may occur in high voltage arrays Charging and arcing may occur	May affect power output Loss of transmission; outgassing source
Polymer Films	Organic binders erode, leaving pigment particles	Darkening, esp. when contamination is present	Some degradation noted at high levels	Charging and arcing may occur with non-conductive coatings	May cause severe degradation of solar absorptance; outgassing source
Thermal Control Coatings					



Materials for Integrated Vehicle Health Monitoring (IVHM)

- Human rated systems have to be highly reliable
- Propulsion systems must be reusable -- capable of multiple starts and stops
- Life prediction techniques must be highly reliable
- Structural health monitoring must be automated
 - Monitoring from ground would take too long during interplanetary travel
 - Need for self-diagnosis and self-correction
- Materials challenges: Examples
 - Lightweight sensors embedded in structures-- fiber optics, piezo-electric materials
 - Nano-materials and nano-sensors
 - Biomimetic materials – materials that can heal themselves when damaged



In-situ Materials Utilization



- Extended stays on the moon or Mars require in-situ resource utilization– to reduce costs
- There are many potentially useful materials on the Moon and Mars– see table below
- Advanced technology must be developed to utilize these resources

Location	Resources	Potential use
Moon		
<ul style="list-style-type: none"> • Environment • Atmosphere • Surface 	Vacuum, 1/6 gravity None Soil Melted sintered soil Lava tubes Metals Non-metals Oxygen Water ice Hydrogen	Materials processing ---- Radiation shielding Construction Thermal shielding Construction Solar cells Propellant, life support Propellant, life support Propellant
Mars		
<ul style="list-style-type: none"> • Environment • Atmosphere • Surface 	1/3 gravity, near vacuum Carbon dioxide components Nitrogen, argon Soil Melted sintered soil Metals Water ice (permafrost)	Materials processing Propellants, life support, plastics Life support Radiation shielding Construction Construction Propellant, life support



Advanced Materials Technologies for Space Exploration



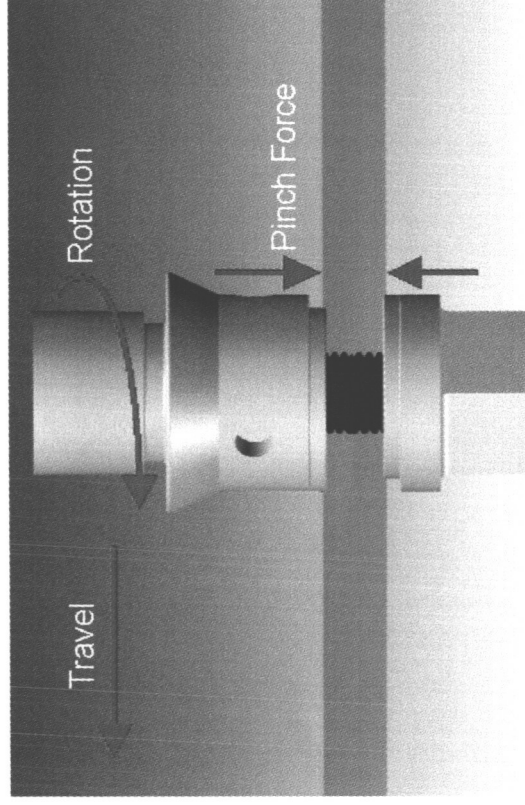
- Metallic alloys resistant to hydrogen, oxygen– high specific strength
- High temperatures materials for thrust chambers and nozzles – MMC, CMC
- High temperature materials for reactors and pumps
- Radiation shielding materials for nuclear propulsion
- Materials to resist space environmental degradation in space systems
- Lightweight, high strength materials for structures and cryotanks– PMC, MMC, Al-Li
- Coatings for stability and thermal management in vacuum
- Lightweight TPS materials for heat shield – aerogels
- Lightweight cryogenic insulation materials
- Smart materials for deployable structures
- Nanostructured materials and coatings
- Carbon nanotube reinforced polymers and metals
- Lightweight sensor materials – fiber optics, piezoelectric, temperature sensor
- Biomimetic materials – self diagnosis and self healing
- In-situ materials utilization – use of Lunar and Mars regolith for construction, radiation shielding, propellant production, etc.



Advanced Processing Technologies for Space Exploration



- Net shape fabrication -- reduce part count
- Rapid prototyping
- Powder metallurgy processing
- Advanced coating techniques – CVD, PVD, Plasma
- Friction stir welding
- Out-of-autoclave curing of PMCs
- Composite fabrication techniques
- Materials processing in space
- Repair technology in space
- Nanomaterials processing techniques
- Laser processing of materials
- Process modeling
- Process development and automation for processing Lunar and Mars regolith



Self Reacting Friction Stir Welding



Summary



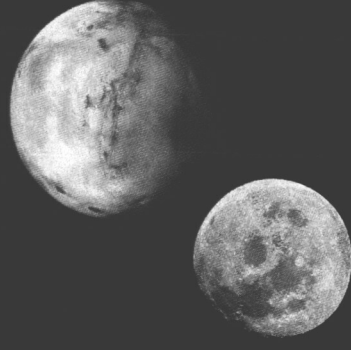
- The new vision of space exploration encompasses a broad range of human and robotic missions to the Moon, Mars and beyond
- Extended human space travel requires high reliability and high performance systems for propulsion, vehicle structures, thermal and radiation protection, crew habitats and health monitoring
- Advanced materials and processing technologies are necessary to meet the exploration mission requirements
- Materials and processing technologies must be sufficiently mature before they can be inserted into a development program leading to an exploration mission
- Exploration will be more affordable by in-situ utilization of materials on the Moon and Mars



Summary (Cont'd)



- **Materials challenges for building space systems: Examples**
 - Lightweight, high strength metallic alloys, ceramics and composites
 - High temperature materials for thrust chamber, nozzle, and fusion reactor
 - Radiation shielding and space environment resistant materials
 - Materials for improved thermal management
 - Nanomaterials for sensors, coatings and structures
 - Smart materials for deployable structures
- **Processing challenges: Examples**
 - Net shape fabrication and rapid prototyping
 - Powder metallurgy processing
 - Friction stir welding
 - Composite fabrication -- out of autoclave curing
 - Nanotechnology
 - In-space manufacturing and repair technologies
 - Process modeling and automation



*It is not really necessary to look too
far into the future; we see enough
already to be certain that it will be
magnificent. Only let us hurry and
open the roads.*

Wilbur Wright

